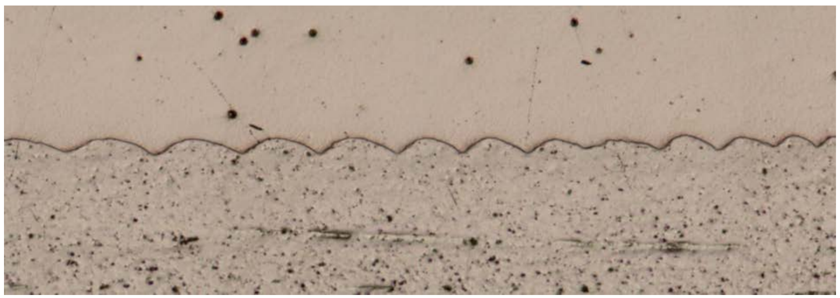
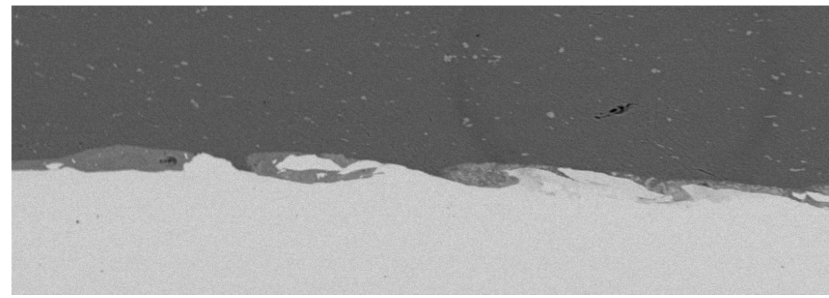
Collision Welding of Dissimilar Materials by Vaporizing Foil Actuator: A Breakthrough Technology for Dissimilar Materials Joining





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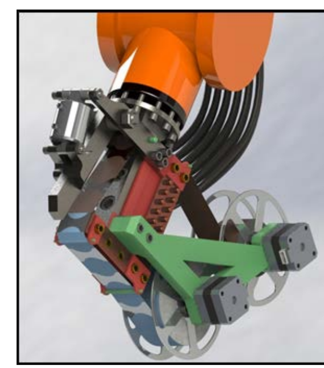
The Ohio State University



THE OHIO STATE UNIVERSITY

COLLEGE OF ENGINEERING

Project ID: LM086

Overview

Timeline

- Start: October 2013
- End: June 2016
- Percent complete: 100%

Budget

- Total project funding: DOE share: $568,499

Barriers & Targets

- Barriers–Versatile methods for joining dissimilar metals.
- Adhesives have low peel strength; we hope to do better
- Heat affected zones and distortion are artifacts of fusion welding we can do away with.

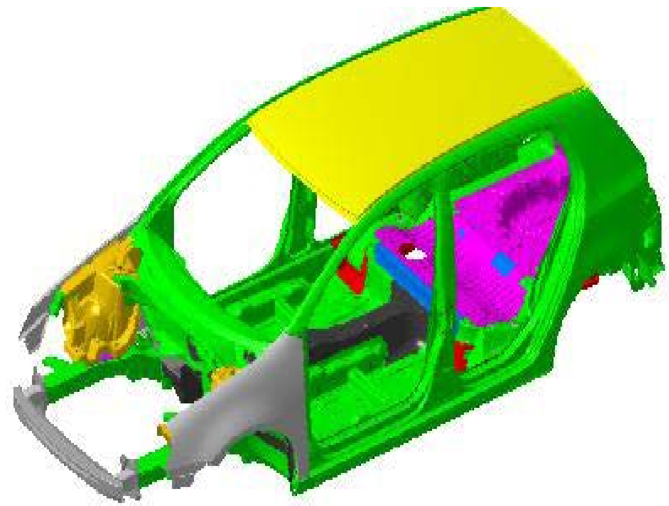
Partners

- Honda: Materials selection and procurement, industrial adaptation
- Alcoa: Materials procurement
- Tier 1 supplier and Equipment builder being engaged now

Relevance

Objectives

- To reduce vehicle weight by optimizing material selection for various parts of the structure
- To incorporate metals with high strength-to-weight ratios: high-strength steel, aluminum, and magnesium
- To enable dissimilar metal joining by Vaporizing Foil Actuator Welding (VFAW)
- Current phase:
  - ❖ To characterize 5 downselected material systems and understand their failure mechanisms
  - ❖ To develop a commercialization plan

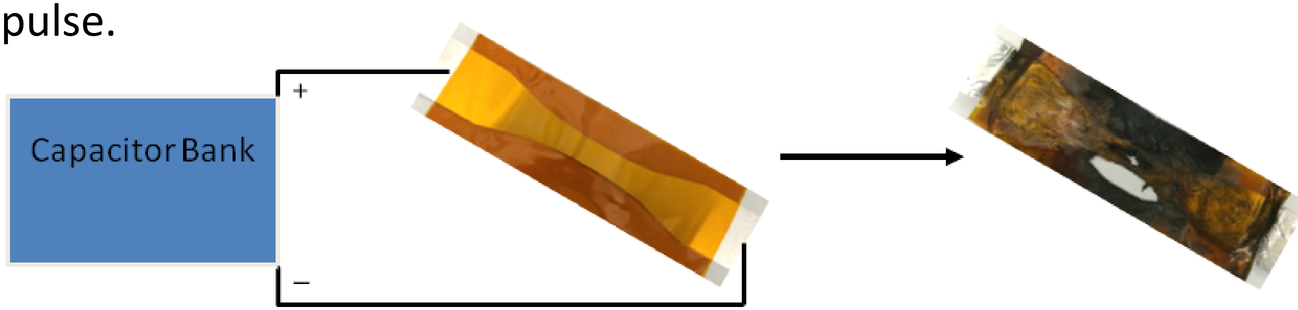


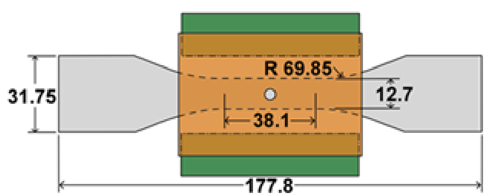
Uniqueness and Impacts

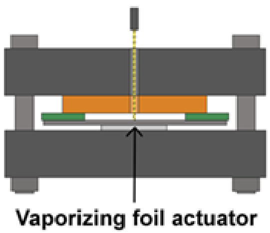
- Uniqueness: VFAW entails miniaturization of impact welding a typical industrial scale
- It can enable joining of dissimilar metals for creating multimaterial structures
- The 2nd phase of the project also aims to study corrosion mitigation strategies for such structures

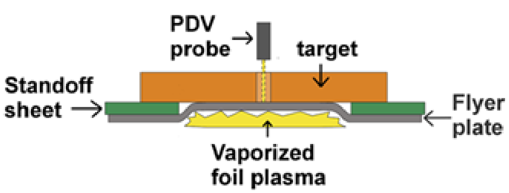
Approach: Basic Method of VFAW

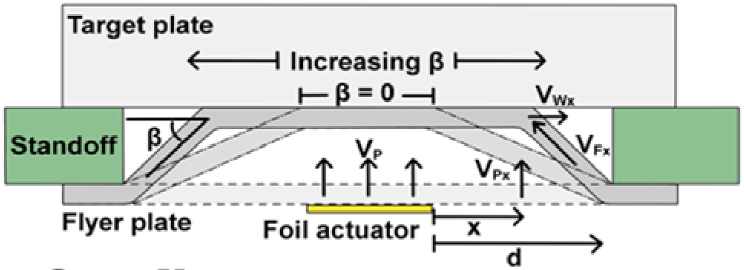
When energy is deposited at a very high rate, a thin conductor can be heated far above its energy of sublimation due to the constraint of inertial and magnetic forces. When these forces let go, the conductor vaporizes and the stored energy is released as a pressure pulse.

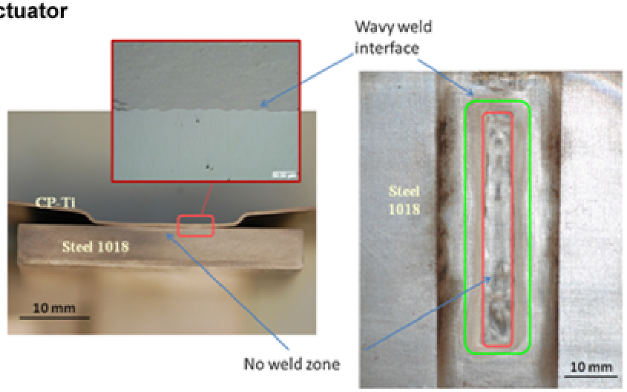




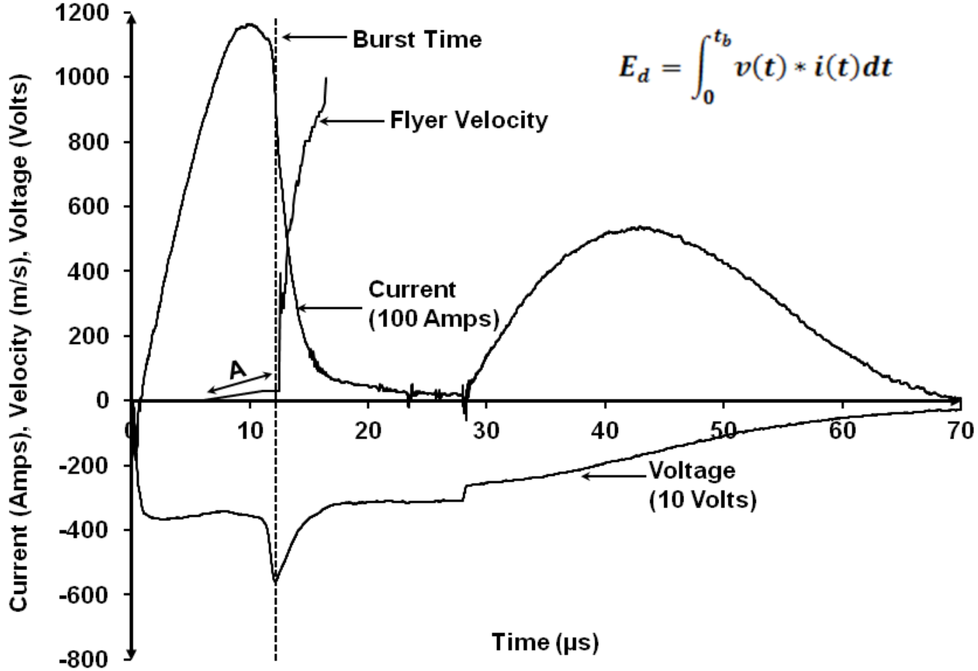


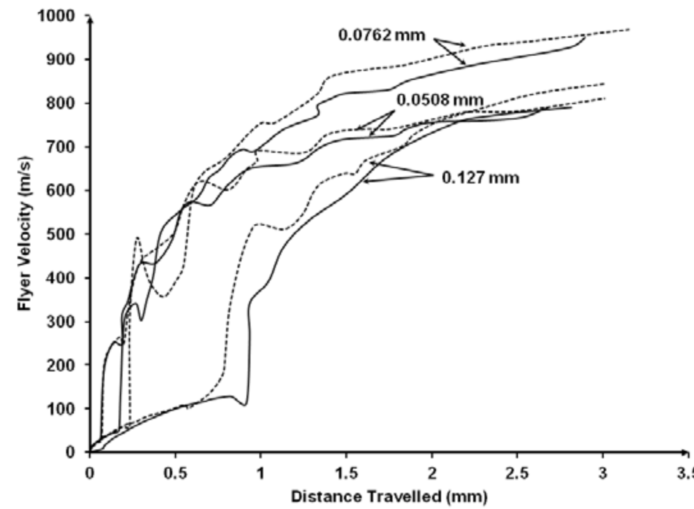


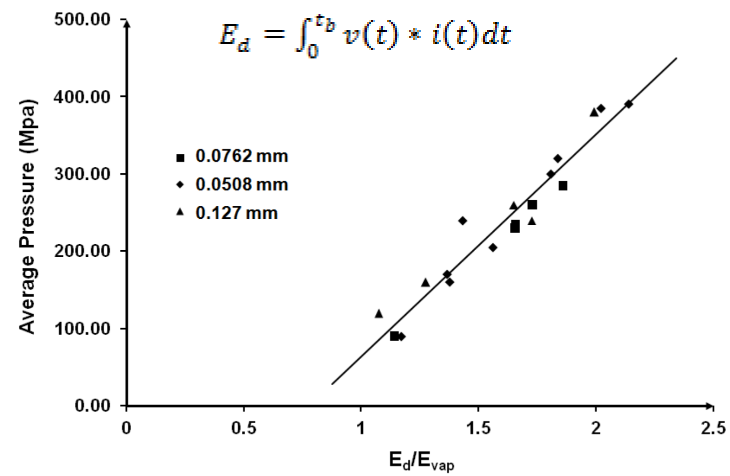




Approach: Process Detail



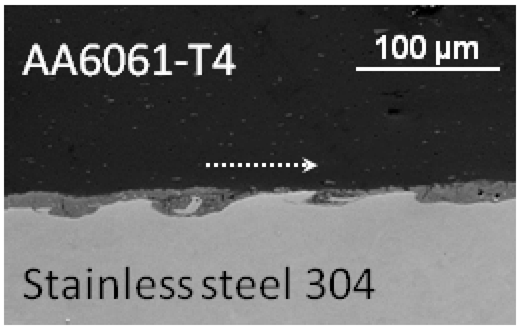




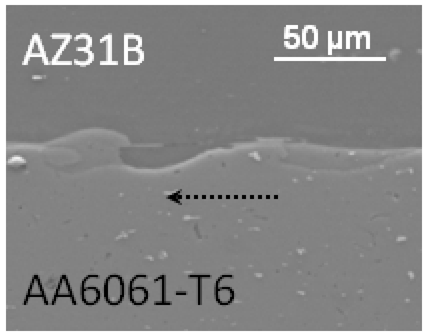
Vivek, A., S R Hansen, and Glenn S Daehn. 2014. "High Strain Rate Metalworking with Vaporizing Foil Actuator: Control of Flyer Velocity by Varying Input Energy and Foil Thickness." *The Review of Scientific Instruments* 85 (7) (July): 075101. doi:10.1063/1.4884647. http://www.ncbi.nlm.nih.gov/pubmed/25085167.

Approach: Dissimilar Welds

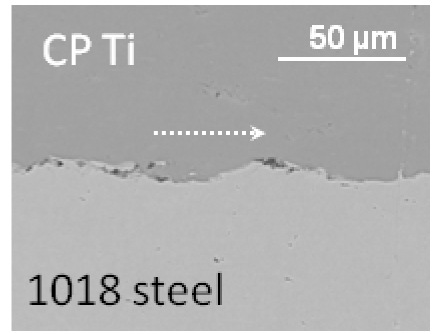
Cross sections and peel strengths of early welds:



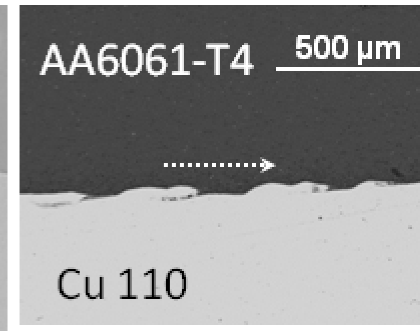
16 N/mm



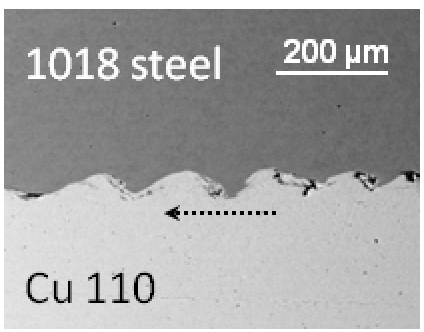
3 N/mm



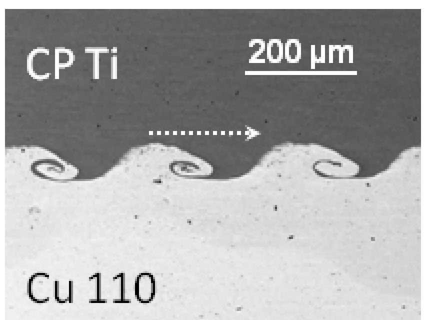
8 N/mm



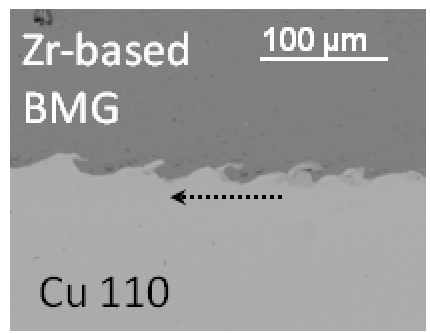
Failed in aluminum



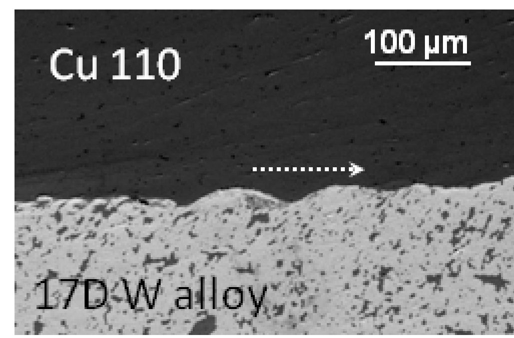
Failed in copper



Failed in copper



Failed in copper



Failed in copper

Approach

<u>Year 1: Selection of materials and systems</u>

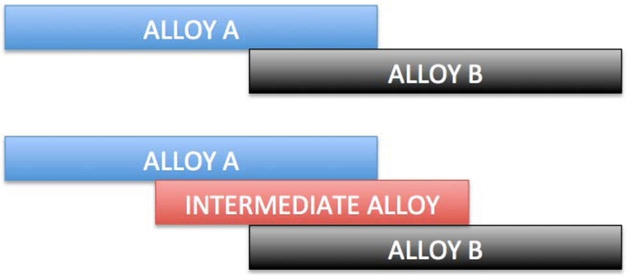
•Goals: Industrially useful strong and corrosion resistant desired couples

•Honda, EWI, and Johnson Control Inc. assist in selection of 1mm thick sheet alloys and corrosion strategies.

•Pairs to be joined:

Al-Fe, Fe-Mg, Mg-Al and Fe-I-Al, Mg-I-Fe

•When corrosion potentials <~0.25 V different, intermediate layer may be needed.
3-layer bonding is feasible based on preliminary work.



<u>Year 2: System joint testing and characterization</u>

•Microscopy: optical microscopy, SEM, EDS

•Mechanical testing: lap shear, peel

•Corrosion testing: B-117 (with and without e-coating)

•Characterization of corrosion-tested samples: mechanical testing and microscopy

Approach

Year 3 (extension): Further study of failure mechanism

- Goals: Strategy for mitigating corrosion based on understanding of corrosion and failure mechanisms.
- Previous work indicates 4 factors which may accelerate corrosion.
- 9 cases are being corrosion-tested to help study the effects of the 4 factors
- Fractography

Scale up and commercial viability

- Ongoing interactions with Honda will keep work guided to utility

Small efforts in: determining limits of vaporizing foil method with respect to geometries possible and length and area of foil that can be vaporized and developing a design methodology.

- Work is underway to commercialize the technology through collaboration with equipment builder, Coldwater Machine Company, and automotive tier supplier, Magna International Inc.

Milestones

Period	Task	Status
Year 1	Selection of 15 material combinations	Completed
	Screening test of the 15 material combinations	Completed
	Downselection to 5 material combinations	Completed
	Microscopy/microstructural analysis	Completed. Further work ongoing
Year 2	Mechanical testing	Completed. Further work ongoing
	Corrosion testing	Completed. Further work ongoing
	Microscopy of corrosion-tested samples	Completed
	Mechanical testing of corrosion-tested samples •Retain 80% strength	Completed. 80% goal achieved for 5 out of 7 material systems
	Developing techniques and fixtures for industry readiness	Completed
Year 3	Investigate corrosion and failure mechanisms by corrosion and mechanical testing	Completed
	Fractography/microscopy	Completed

Technical Accomplishments and Progress

- Five out of seven material pairs retained 80% lap-shear strength through 30 days of ASTM B117 salt-spray corrosion testing, with protective coating.

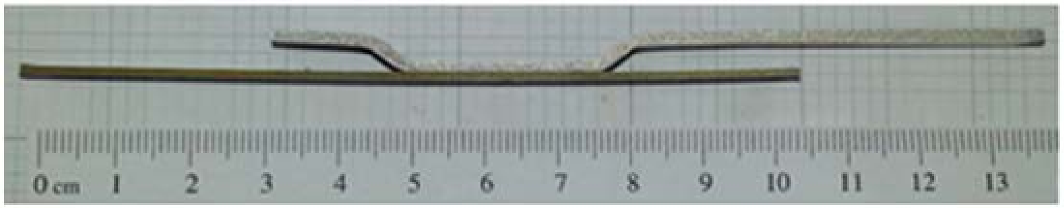
From last year:	From this year:
•AA6061-T4/DP780*	•AA5052/JAC980*
•6061-T4/JAC270F*	•AA5052/JSC1500*
•AA6061-T4/AM60B	•AA6111-T4/JAC980*
	•AA6111-T4/JSC1500

* 80% strength retained

- Weld interfaces without continuous IMC layer were obtained
- AA6061-T4 flyer up to 2 mm thick was welded to DP780 steel
- Semi-automated pedestal spot welder is built and operational
- Commercialization of the technology is underway through collaboration with Coldwater Machine Company (welding equipment maker) and Magna International Inc. (automotive tier supplier).
- Spot welding of Al/Fe was achieved at ~2.5 kJ input energy (~1/10 of RSW), thanks to a new high-efficiency pulse power supply and welding configuration.

2 mm thick Al flyer

- Thickest Al flyer successfully welded to steel

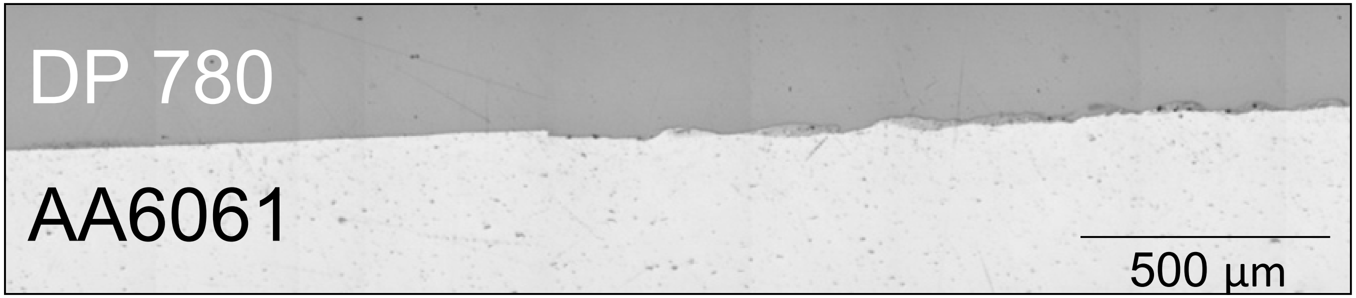


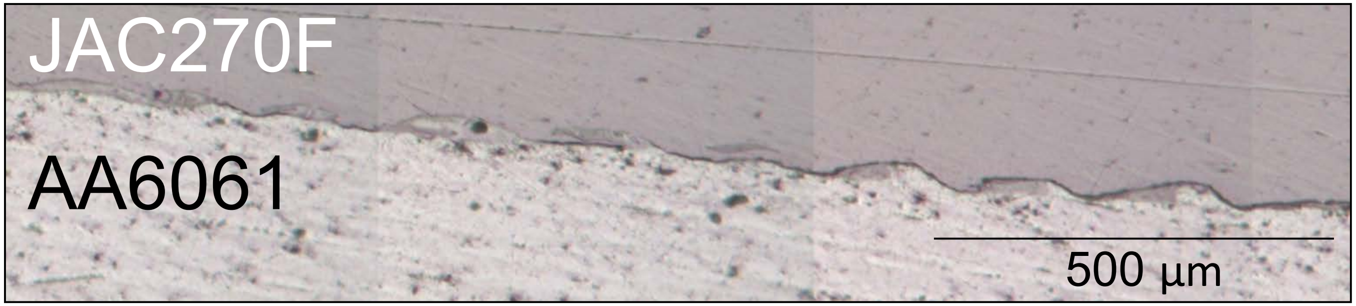
2mm thick Al6061-T4 welded to DP780 steel (Impact speed = 660 m/s)

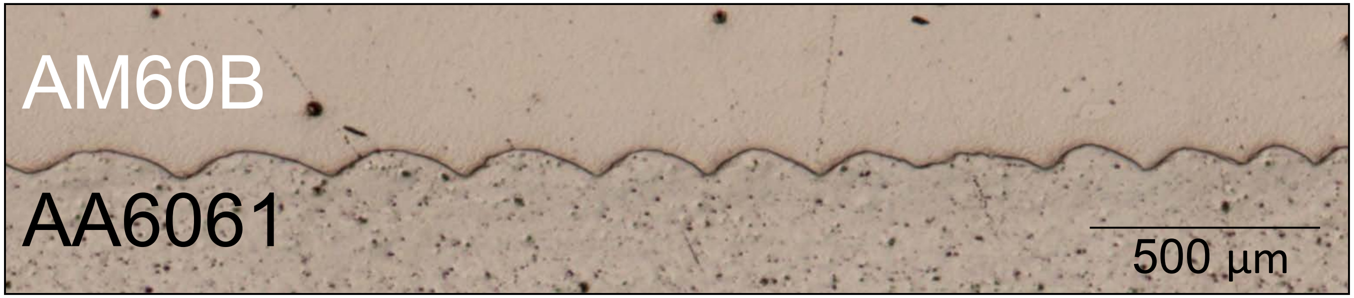
Lap-shear: 5000 N

Peel: 25 N/mm

Al/Fe and Al/Mg joints

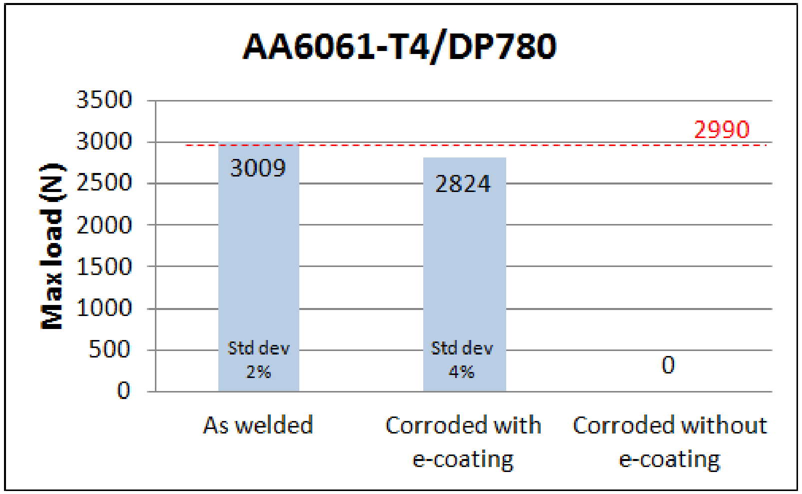


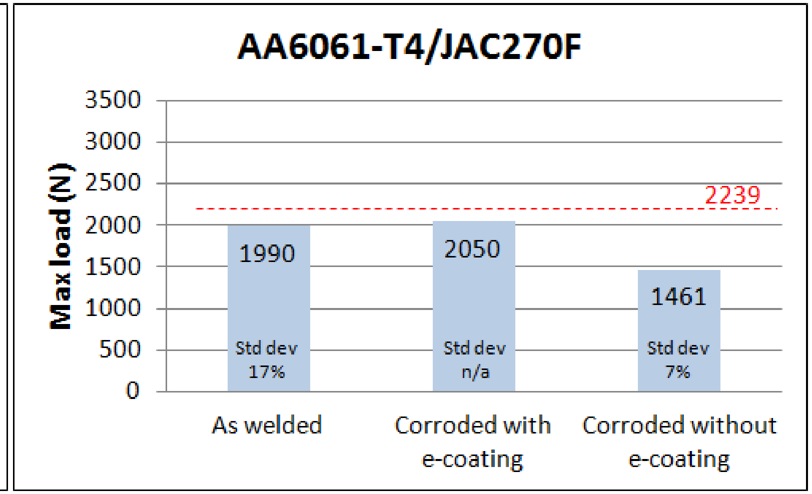


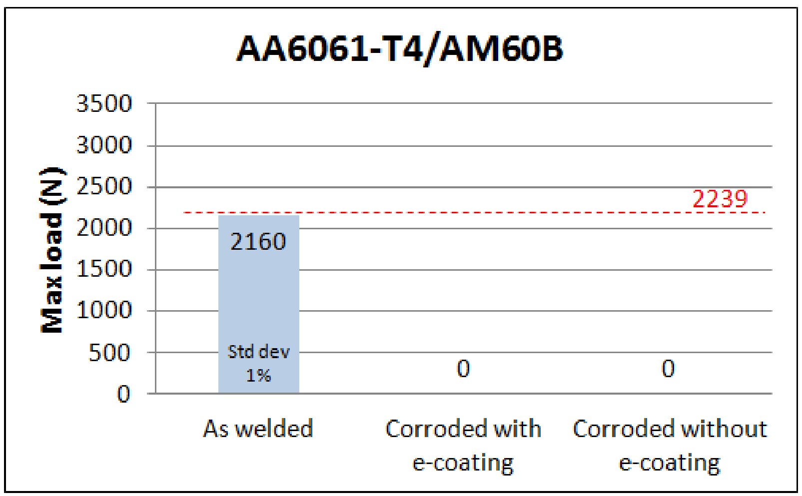


Al/Fe and Al/Mg joints

- Corrosion and mechanical testing of Al/Fe and Al/Mg joints







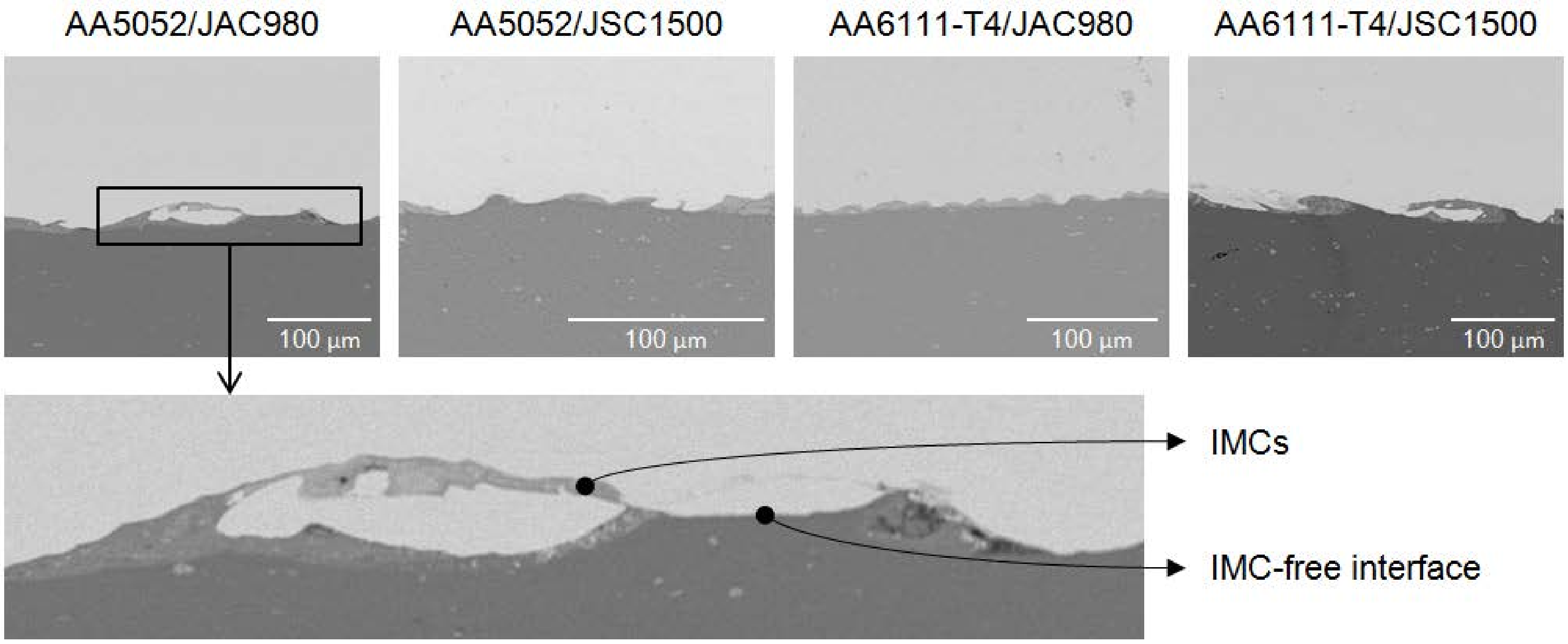
Red dashed line indicates the expected failure load if failure occurs in a base material, without any weakening effects

* Asterisk indicates that the majority of the samples failed in a parent material, thus the true shear strength should exceed the valued reported here.

Standard deviations (Std dev) are indicated by percentage

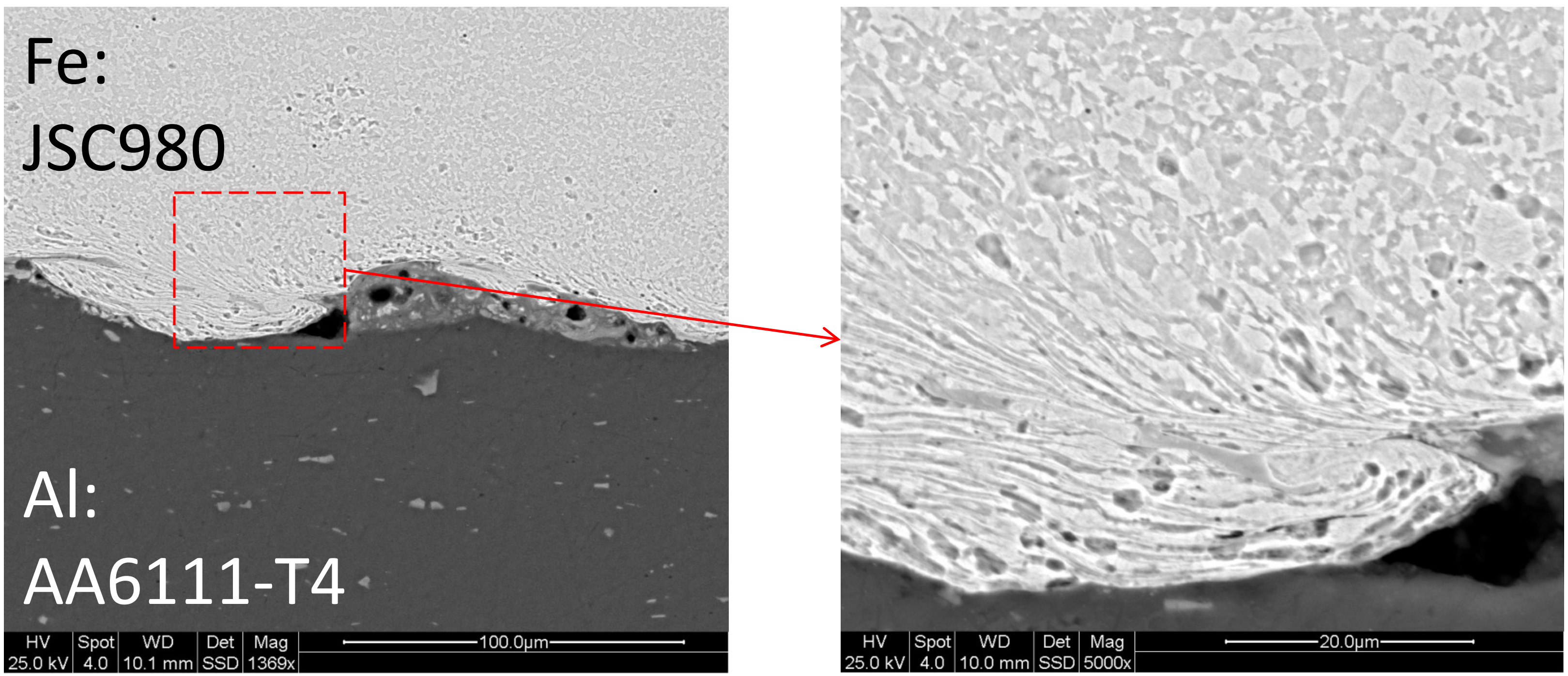
Al/Fe joints of high-strength alloys

- Weld cross sections of four high-strength Al/Fe combinations
  - IMC-free regions were obtained at the interfaces of all four combinations



Al/Fe joints of high-strength alloys

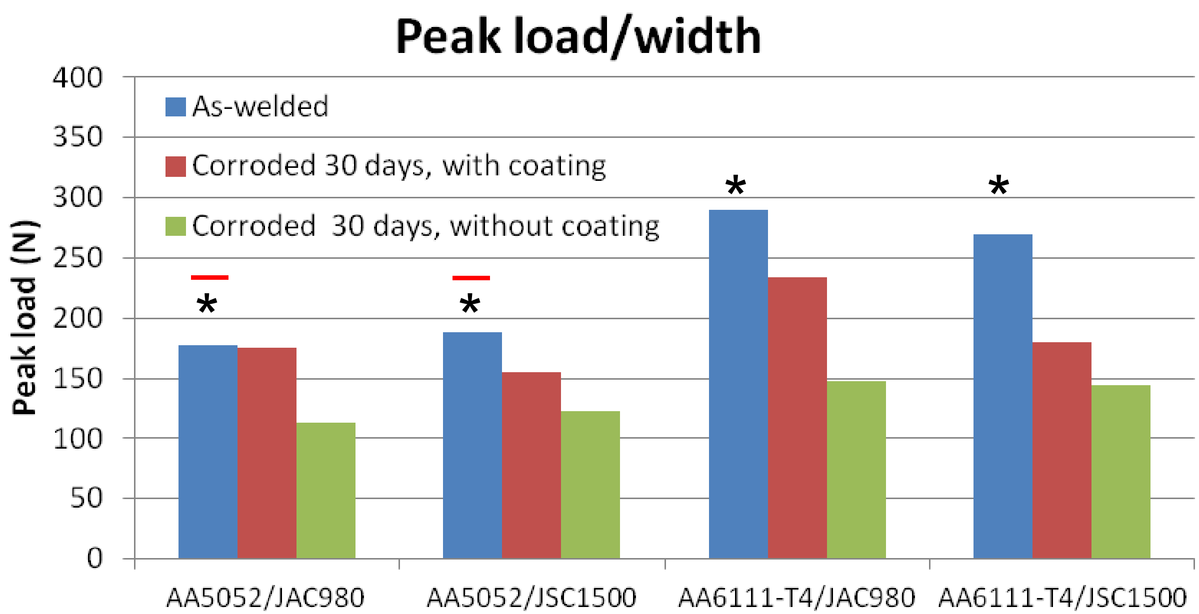
- Refinement and elongation of grains near interface



Al/Fe corrosion testing

- Corrosion and mechanical testing
  - > 80% strength retained for three of the coated Al/Fe combinations (lap-shear)
  - Differences in open cell potentials was small (≤ 60 mV) among base metals

Metal	OCP (V SCE)
AA5052	-0.746
AA6111-T4	-0.698
JAC980	-0.758
JSC1500	-0.690



0.94 mm thick AA5052 1 mm thick AA6111-T4

* = Strength of base Al

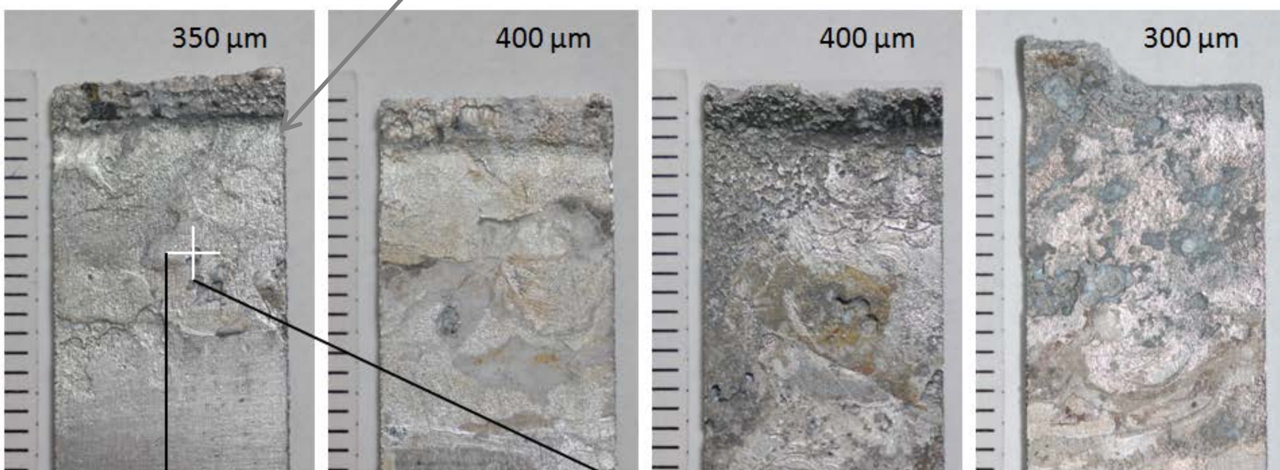
— = Peak load of FSW AA5754/DP600 with a 2mm-thick Al sheet (Shen et al., 2015)

Shen, Z., Y. Chen, M. Haghshenas, and a.P. Gerlich. 2015. "Role of Welding Parameters on Interfacial Bonding in Dissimilar Steel/aluminum Friction Stir Welds." *Engineering Science and Technology, an International Journal* 18 (2): 8–15. doi:10.1016/j.jestch.2014.12.008. http://linkinghub.elsevier.com/retrieve/pii/S2215098615000105.

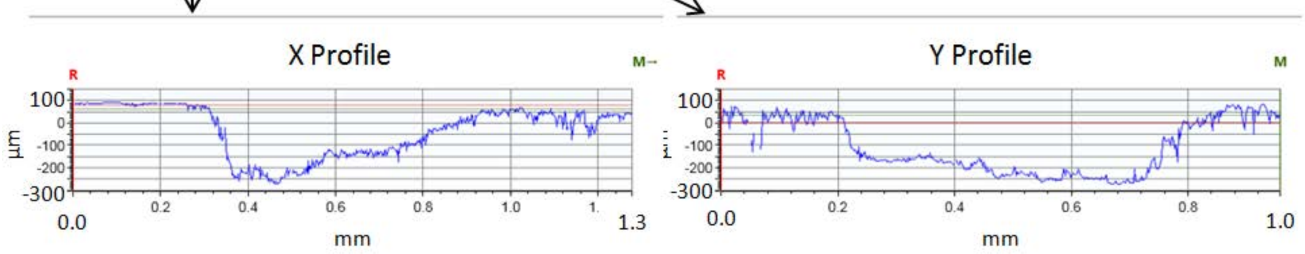
Corrosion of base Al

Sample which failed in Al in lap-shear

Underside of corroded Al



Profiles of pit



Corrosion mechanism

Case	Schematic	Galvanic couple	Jetted materials	Strain/ thinning	Crevice
1. As welded		√	√	√	√
2. Crevice removed		√	√	√	
3. Crevice removed + jet removed		√		√	
4. Flattened		√	√	√	
5. Overhang cut loose			√	√	

= jetted materials   = brush damage

Corrosion mechanism

Case	Schematic	Galvanic couple	Jetted materials	Strain/ thinning	Crevice
6. Overhang w/ jet removed				√	
7. Base materials					
8. Base mat. w/ brush damage					
9. Al-Al weld			√ (not galvanic)	√	

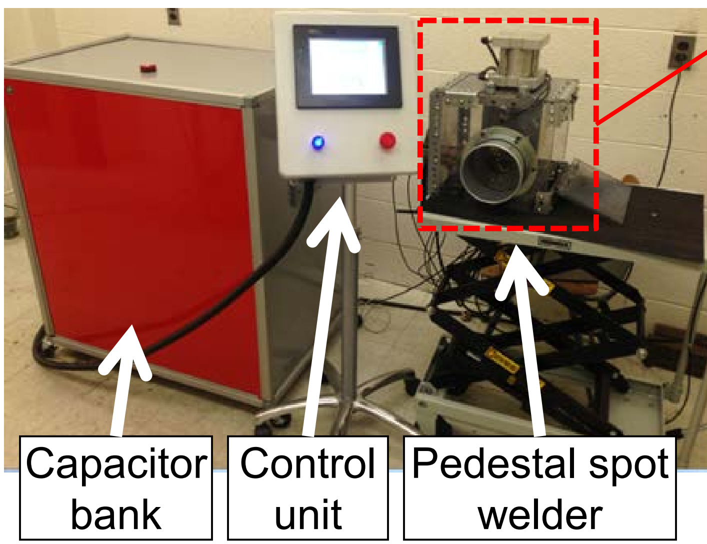
= jetted materials   = brush damage

Pushing for industry readiness

Engaging industry partners

- 80 customer-discovery interviews through I-Corps @ Ohio
- Collaboration with
  - Honda (fatigue testing)
  - Coldwater (welding equipment)
  - Magna (component)

Low-inductance capacitor bank



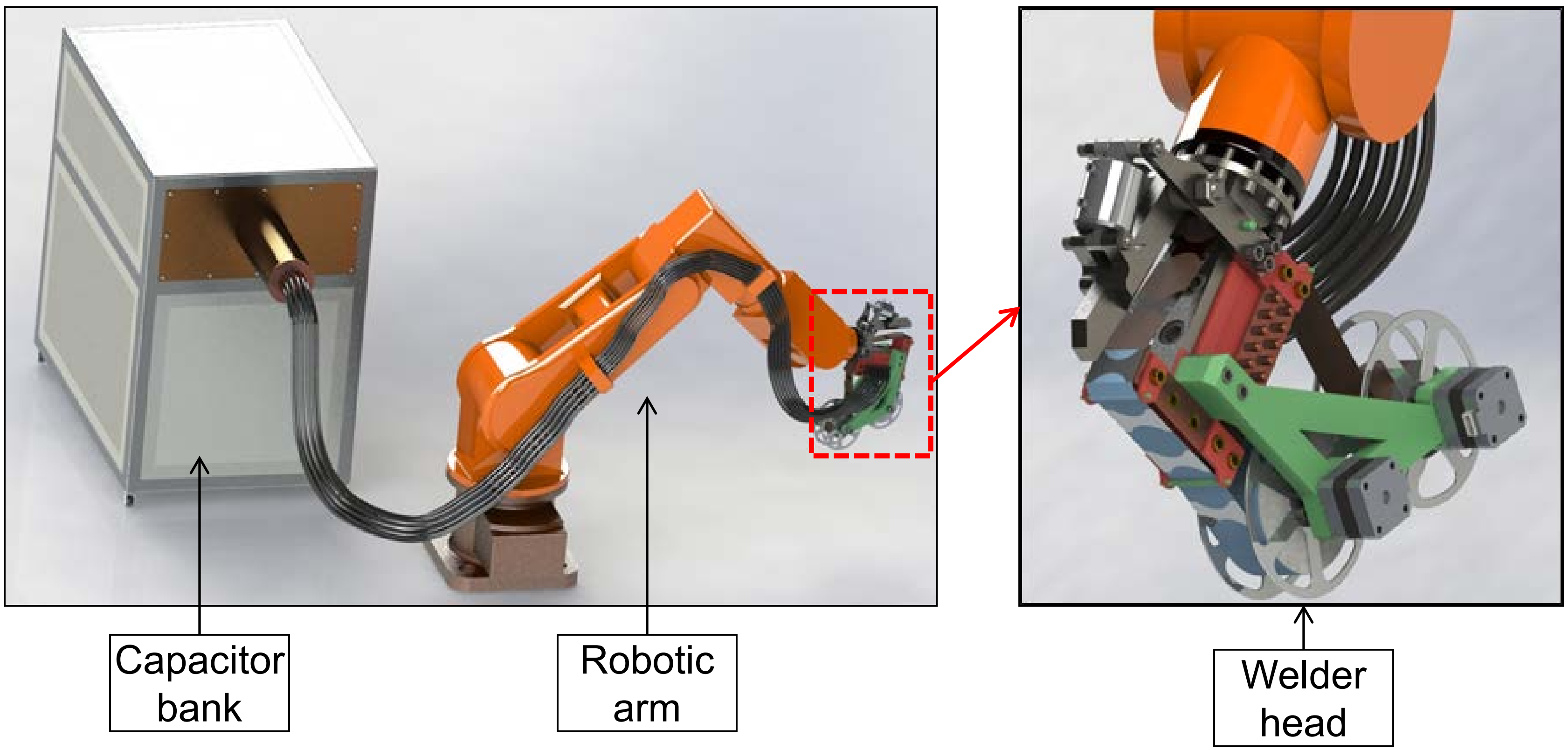
- Short current rise time
- Spot weld at ~2.5 kJ (~1/10 of RSW)

Semi-automated pedestal spot welder

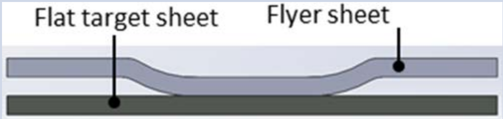
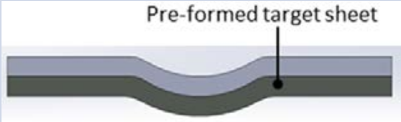
VFAW spot weld
- Materials: AA5052/JSC590
- Input energy: 2.6 kJ
- Failure load: 6000 N

Pushing for industry readiness

Plans for robotic welder



Answers to Reviewers' Comments

Comment	Response
"The need for a standoff gap appears to be problematic in automotive design"	In related work, we are devising new welding geometries where the standoff gap is provided by a pre-formed target, leaving no open gap at the end.  vs. 
"Collaborators have primarily provided opinions and guidance, rather than shared responsibility for the research."	Honda is becoming deeply engaged and initiating studies on fatigue resistance of welds. This must be understood prior to commercialization.
"there was little interaction with a supplier to commercialize this process"	We are engaging new partners to help commercialize the technology: a welding equipment manufacturer, Coldwater Machine Company, and an automotive tier 1 supplier, Magna International Inc.

Collaboration

Honda America: Duane Detweiler, Tim Abke, Pete Edwards (Honda R&D and engineering)
Role: Benchmarking of VFA spot welds against resistance spot welds.
Guidance with material selection and procurement.

Alcoa: Dan Bryant and Edmund Chu (Alcoa)
Role: Material selection and procurement.

Ohio State University, Fontana Corrosion Center: Prof. Rudy Buchheit and Prof. Jen Locke
Role: Will help with corrosion testing of coated and uncoated welds and understanding corrosion mechanisms at play

Technical Summary/Future Work

- Vaporizing foil actuator welding (VFAW) produces robust dissimilar-metal welds with favorable microstructures
- 80% strength retention through corrosion testing was achieved by protective coating for 5 out of 7 pairs tested
- Investigation on corrosion and failure mechanisms is in progress and will continue
- We continue to push for industry readiness.
  - Semi-automated pedestal welder is built and operational
  - Development of welding done in industrially relevant geometries continues
  - Using a faster capacitor bank, spot welding was achieved using ~2.5 kJ (about 10% of energy required for Resistance spot welding)
  - Work is underway to commercialize the technology through collaboration with equipment builder, Coldwater Machine Company, and automotive tier supplier, Magna International Inc.